United States - Canada Symposium
North American Climate Change and Weather Extremes

A RESEARCH AGENDA

October 6-8, 1999

Atlanta, Georgia

Sponsored by

Environment Canada

Climate Change Action Fund (Canada)

U.S. Environmental Protection Agency

U.S. National Weather Service

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PREFACE

A three-day workshop on climate variability and change and extreme weather events in North America was held in October 1999 in Atlanta, Georgia. The workshop was a bi-national effort conducted under the auspices of a United States - Canada agreement fostering cooperation on activities of mutual interest in the areas of climate, meteorology, and hydrology. Environment Canada, the Climate Change Action Fund (Canada), the U.S. Environmental Protection Agency, and the U.S. National Weather Service jointly sponsored the meeting.

The purpose of the symposium was to foster dialogue between resource managers and planners who are affected by extreme events, impacts and adaptation researchers, climate modelers, climatologists, and computer hardware developers. The goal was to identify existing capabilities and near-term needs in understanding weather and climate extremes, that, if met, would improve our ability to assess the human impacts of extreme weather. To advance these goals, the symposium was designed to:

- review current capacities for identifying weather extremes in the climate system;
- assess current understanding of the relationship between weather extremes, climate variability, and climate change;
- examine the vulnerabilities of American and Canadian societies to weather extremes; and
- determine the steps needed to advance the modeling and assessment of weather extremes.

Nearly 85 participants were involved in the three-day meeting. The participants included scientists from a variety of disciplines — climate modeling, climatology, impacts assessment, computer hardware development, physical science, and economics — as well as representatives from the insurance industry, public health officials, and managers of water resources, air quality, transportation systems, and public utilities. A list of symposium participants appears in Appendix B.

From the workshop presentations and discussions we have distilled the following research agenda for future work by climate modelers and impacts researchers. Important knowledge gaps are identified, but no attempt is made to prioritize the research needs (*e.g.,* using "value of information" criteria). We hope that this agenda accurately describes and adequately captures the many research needs and knowledge gaps identified by symposium participants. Also, we hope that this symposium and the resulting agenda help to promote collaborative and multi-disciplinary research and further dialogue across communities of scientists and practitioners in the study of climate and weather extremes.

Janet Gamble
U.S. Environmental Protection Agency

Roger Street
Environment Canada

Joel Scheraga
U.S. Environmental Protection Agency

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THE RESEARCH AGENDA

What is a climate or weather extreme? The answer depends on who you ask.

To the average citizen, an extreme is a weather event or the culmination of a number of contributing events (which in themselves may not be extremes) from which significant negative outcomes — property damage or loss, injury or death — emanate.

To the impacts scientist, an extreme is viewed as an exceedance of some threshold of human, monetary, or environmental impact.

To the climatologist, an extreme is defined according to the probability distribution associated with the occurrence of a particular climate parameter. By definition, the extreme occurs in the tails of the statistical distribution. An extreme defined in this way may or may not have any obvious societal or environmental impacts.

Clearly, there are many definitions of extreme weather events and a real need to develop some agreement that fairly represents, while not losing sight of, each perspective. The local official worried about the flooding of a nearby river, the public health official concerned about possible outbreaks of vector-borne diseases linked to particular climatic conditions, and the climatologist estimating the likelihood of an intense precipitation episode, all have different notions of extreme weather events. Therefore, our understanding of what constitutes an extreme event is most complete when it draws from each of these perspectives.

The 1999 United States - Canada Symposium on North American Climate Change and Weather Extremes evolved from a desire to bring these perspectives together. The symposium was designed to gather people from a variety of scientific disciplines engaged in various aspects of extremes research and representatives of affected communities; to encourage more integrated conceptualizations of the research problems; and to better coordinate the study of weather and climate extremes across communities of researchers.

It is very important that we agree on a consistent definition of extreme events so that we can be assured that we are talking about the same episodes, whether we are concerned with changes in impacts or trends in natural events.

W.D. Hogg
Environment Canada

The ultimate goal was to encourage the development of a shared vision of research needs. This research agenda is an effort to advance the science of climate and weather extremes modeling, the science of impacts modeling and assessment, and the development of the computer capabilities necessary to both, within a context that recognizes the needs identified by the practitioner communities.

We have organized the research agenda in four sections:

- Climate Monitoring and Modeling
- Interface of Climate and Impacts Modeling

- Impacts and Adaptation (with impacts on human health, air quality, water supplies, and infrastructure), and
- Communication Issues

Though the divisions are somewhat arbitrary, we hope that they provide useful organization to a wide-ranging collection of research needs. We hasten to add that such divisions were less evident at the meeting. In fact, the cross-cutting nature of the discussions gives us confidence to suggest that much of the work described here may best be accomplished by integrated teams of investigators drawn from multiple disciplines and paradigms.

The other strong message from the meeting was the reminder that researchers must learn to be more responsive to the needs of practitioners and to address the questions of affected communities. There is significant need for research on issues that lie at the interface of traditional science and the practical needs of local communities, resource managers, planners and developers, property insurers, emergency preparedness officials, and local, state/provincial, and federal policy makers.

CLIMATE MONITORING and MODELING

Workshop participants discussed a number of issues related to data collection, issues of model resolution and scale, and adjustments to data necessitated by changes in measurement practices or changes in coverage of observation systems.

There was wide agreement that collection of and access to high quality climate data, including continued efforts to digitize historical data, is a crucial piece for studies of climate and weather extremes. There was also interest in the continued development of paleoclimatic data as a source of historic information on climatic extremes.

With respect to modeling, there were calls for better simulation of current extreme events, for the systematic evaluation of large numbers of Global Circulation Models (GCMs) to compare how well they perform in simulating extremes, and for developing Regional Circulation Models (RCMs) to "move" within GCMs to follow discrete extreme events such as hurricanes.

Specific suggestions for research related to climate system science included the following:

Monitoring and Data Collection

- Improve access to high-quality, long-term climate data with the time and spatial resolution appropriate for analyzing extreme events.

- Support monitoring efforts such as the Global Climate Observing System (GCOS) through which long-term variability and trends in extreme climate events may best be detected.

- Determine the data needs of the climate change impacts, hazards, practitioners, and modeling communities related to climate or weather extremes and catalogue by sector, by climate or weather variable, by data element (*i.e.,* probability, mean, variance, etc.), and by time frame.

- Increase resolution of both data collection (wider and finer networks of observing stations/satellites and systematic archiving of historical data) and information processing and modeling power. Additional resolution will require modification of algorithms for processes currently parameterized at lower resolutions.

We need to arrest the decay in the Global Climate Observing System, generate high resolution standard climatologies, complete the clean-up of archived observations and analyze those extremes which are deemed critical for climate impacts.

Ian D. Rutherford
Canadian Institute for Climate Studies

- Support programs to digitize the high quality temporal resolution data for North America that remains unused.

- Develop methods that can address the inhomogeneities and biases introduced into observations on thunderstorms and tornadoes by increased population density.

Identifying Extremes from the Historical Record

Better define and identify extreme events using existing instrumental, paleoclimatic and other proxy records to provide a baseline for studies of future extremes in the context of climatic change. Sources include:

- drought records from Eolian sands
- flood records from river and lake sediment
- thaw unconformities from permafrost records (indicating temperature anomalies)
- temperature, precipitation extremes from tree ring records
- outbursts and other flood records in fluvial channels
- melt layers within glacier ice cores

Modeling Past, Present, and Future Extreme Events with GCMs and RCMs

- Determine the capacity of climate models to simulate past and present extreme events and to project future extreme event climatologies.

- Identify climate/weather variables or synoptic conditions that are associated with extreme events and that can be resolved by current GCMs.

- Compare how well a large number of GCMs simulate observations for a defined set of extremes; determine how that set of extremes changes for a canonical climate change simulation, such as $2XCO_2$ for the same GCMs.

- Identify and assess uncertainties introduced through the use of higher spatial and temporal resolution derived from (downscaled from) GCM scale data.

- Identify capabilities and errors in GCM simulations of inter-annual climate variability and/or in replicating ENSO-like behaviors.

- Develop extreme event scenarios based on GCM and RCM outputs that identify the probability or potential frequency of extreme events.

- Develop nested RCMs that can "move" within GCMs to "follow" interesting synoptic scale phenomena such as hurricanes or overlapping zones of vulnerability (such as would be found in a geographically arrayed series of severe weather alert boxes).

Extending hurricane forecasting capabilities

Improve seasonal and interannual forecasts of hurricane occurrence and examination of the relationship between tropical cyclone activity and ENSO (El Niño Southern Oscillation).

Call for Interdisciplinary Research

- Coordinate observations of storms and observations of impacts to facilitate interdisciplinary assessments of the relationship between the two. This can be accomplished by developing coordinated and integrated observation networks across significant natural regions.

- Assess the characteristics of extreme events (*e.g.,* storms; tornados) that are responsible for particular impacts. For example, what characteristics of a tornado are most responsible for damages to buildings: straight-line wind, microbursts, the vortex of the tornado, or some other aspect of the tornado? An understanding of the causes is important for the development of approaches to increase the resilience of systems (*e.g.,* buildings) to extreme events.

INTERFACE of CLIMATE and IMPACTS MODELING

A number of the identified research needs lie at the juncture of climate modeling and impacts modeling. The following suggestions demonstrate the need for better coordinated research across modeling communities.

When an Extreme Becomes a Disaster

Define (for each community) when a climate/weather event becomes an extreme. Conduct research, where necessary, to define thresholds and to determine how thresholds vary across alternative perspectives of what constitutes disaster.

Modeling Joint Probability Events

Investigate extremes of large-area or multi-parameter events. In particular, there are events that have significant impact only with the joint occurrence of special conditions in two or more parameters. (For example, snowstorms followed by rainstorms can lead to flooding.) More attention should be given to "coupled," "complex-composite" phenomena and their attendant joint / conditional probability distributions. New approaches and statistical tools are needed to document and analyze these joint probability events and to assess the composite impacts of high-probability, low-consequence events — *i.e.*, the simultaneous occurrence of multiple weather events impacting multiple human/social conditions to produce extreme vulnerability. Extreme events often occur as "complex-composites" that involve a series of joint and conditional probabilities which are difficult to model and for which uncertainty is difficult to assess.

IMPACTS and ADAPTATION

Research suggestions for impacts and adaptation focused on model capabilities, risk perception, building the resilience of systems, and evaluating adaptive responses. Identified research needs included:

Impacts Assessment and Modeling

- Develop more sophisticated impact models that incorporate operational knowledge, deal with uncertainty and extremes, incorporate land use changes, combine physical impacts and management, and incorporate more socio-economic information and that do not assume *ceteris paribus* conditions.

- Improve projections of future socio-economic factors such as population, population distribution, demographics, wealth, etc., that may modify the climate-society relationship over time.

- Conduct a national risk assessment of physical and social systems and the built environment (*e.g.*, number of buildings in a flood prone area, their level of vulnerability, etc.) to provide an understanding of what is at risk and how the risks arise. Components of the assessment must be conducted at a scale that can provide useful information to the local officials.

Understanding Risk Perception

Assess public perceptions of the risks associated with various extreme climatic conditions.

Building Resiliency

- Develop mechanisms for including a consideration of vulnerability to extreme events into any planning and design decisions.

- Develop decision support systems to assist local stakeholders in factoring in various reductions in vulnerability in community planning and design decisions.

Evaluating Adaptation

Systematically evaluate programs designed to contribute to disaster resiliency by:

- Conducting "post audits" to evaluate and identify successful and unsuccessful adaptations in the aftermath of their application.

- Identifying "triggers" that prompt the public and local governments to take actions to reduce vulnerability to extreme climate/weather and evaluate how effectively and how long new adaptive measures or regulations rules are maintained or enforced.

IMPACTS on HUMAN HEALTH

The focus of suggestions for impacts research in human health included morbidity and mortality effects of extreme temperatures, air pollution related to extreme weather conditions, and vector-, water-, and food-borne diseases. In addition, research on environmental refugees, adaptive responses, and psychological impacts was also suggested.

Extreme Event-Related Mortality and Morbidity

Determine the short-term (*e.g.*, drowning), medium-term (*e.g.*, diarrhea associated with contaminated water), and longer-term (*e.g.*, psychological disorders) health effects associated with extremes such as flooding or drought events, wildfires, or tornadoes. Examine how global environmental changes, including land use changes and climate change affect these estimates.

> *"Environmental refugees" could potentially present the most serious health consequences of climate change, considering the associated risks that stem from overcrowding, virtually absent sanitation, scarcity of shelter and natural resources, and heightened tensions potentially leading to conflict.*
>
> Jonathan Patz
> Johns Hopkins University

Environmental Refugees

Evaluate the consequences of displacing human populations in major flooding events (*i.e.*, environmental refugees).

Research on Extreme Temperatures and Morbidity and Mortality

- Determine the relative balance between changes in cold- and heat-related mortality associated with climate change.
- Determine which geographic areas are most vulnerable to thermal extremes and how land use patterns affect that vulnerability.
- Measure the extent to which thermal extremes result in deaths among very frail or ill populations (*i.e.,* displace mortality by a few days or months).
- Evaluate how populations acclimatize to warmer climates and how acclimatization can be accounted for when estimating future heat-related mortality.
- Examine which physical conditions are associated with heat stress in summer and cold stress in winter and how their incidence changes as the earth warms.
- Develop more extensive net annual mortality estimates stratified by season, cause of death, and other important confounders.

Extreme Weather and Air Pollution Health Effects

Evaluate the relationships between extremes in temperature, humidity, and other weather variables and air pollution-related health effects.

Vector-, Water- and Food-Borne Diseases and Climatic Extremes

- Study the relationship between climatic extremes and those vector-borne diseases that appear to have a link to climatic conditions, *e.g.*, hantavirus, leptospirosis, dengue, St. Louis Encephalitis, especially links between climatological and ecological changes that create the necessary conditions for disease spread.
- Examine water contamination in flood

events and associated water- and food-borne illnesses.

- Determine how changes in the hydrological cycle, water temperatures, frequency of extreme weather conditions (*e.g.*, hurricanes), sea level rise, and land-use changes affect water-borne disease risks (from both freshwater and marine environments).

- Determine if there are relationships between the incidence of water-borne diseases and the frequency and intensity of climatic extremes. Where indicated, characterize those relationships.

- Investigate how the reporting of water-borne diseases can be improved to better understand contributing or causal factors.

Psychological and Sociological Impacts of Extremes

Identify and analyze psychologic and sociologic impacts of extremes, *e.g.,* post traumatic stress disorder.

Human Adaptive Responses

- Evaluate what will happen to the effectiveness of vector-management strategies (*e.g.*, spraying with pesticides) and medical treatments (*e.g.*, antibiotics) over time with changes in the frequency and intensity of climatic extremes.

- Examine the potential consequences (both positive and negative) of various adaptive strategies that mitigate adverse consequences associated with climate extremes.

- Evaluate the utility (especially for decision makers) and the costs associated with enhanced monitoring and surveillance activities and extreme weather warning systems.

IMPACTS on AIR QUALITY

Research needs related to extreme events and air quality focused on three areas: air quality standards and indices, modeling, and the impact of extremes on emissions from biogenic sources, wildfires, and during stagnation episodes.

Air Quality Standards / Indices

- Develop consistent air quality indices across disciplines and across jurisdictions, and develop an integrated standard for use in North America.

- Examine the impacts of projected changes in climate including the effects of extremes on air pollution control programs and identify adaptations that may be needed to address these implications.

- Examine the implications of climate / weather change for meeting air quality standards in the future.

- Investigate and develop multiple-benefit strategies for greenhouse gas reduction that simultaneously realize reductions in air pollution (or vice versa). Such strategies avoid piecemeal regulation and yield more efficient and effective overall results.

Modeling Needs

- Improve modeling of surface-boundary layer, clouds, winds, etc. in the context of extreme climatic conditions.

- Improve estimation and modeling of the global transport of air pollution in the context of extreme climatic conditions.

- Develop emissions data, which currently is either unavailable or of such poor quality as to be an impediment to model application.

- Develop methods for merging the time frames associated with climate scenarios (50 or more years) with air quality emission projections (maximum of 15 years). This is just one example of the multitude of temporal, spatial, and magnitude ambiguities that plague the development of linkages between air quality and climate change.

Role of climate and weather extremes in biogenic emissions, secondary pollutants, stagnation episodes, wildfire

- Biogenic emissions are sensitive to meteorological influences and tend to peak in the summer months. Determine how climate extremes affect biogenic sources and emissions over time.

- Examine how secondary air pollutants are affected by climate extremes, and how climate extremes may affect particle size, transport, and chemical composition.

- Evaluate the implications of long-term climate change, including changes in daily, seasonal, and interannual variability and extreme events, for stagnation episodes and air quality. Determine which aspects of climate variability are most important for stagnation frequency.

- Determine what the consequences of altered drought and fire regimes and land-use changes on air pollutant concentrations are, and which areas are most likely to be affected.

IMPACTS on WATER SUPPLIES

In discussions on the impact of extreme events on water supplies a number of areas for research were identified, including: data and modeling needs, development of strategies for water management and water pricing, assessing the interaction of the impacts of extremes on water supplies with impacts of other stressors, and evaluation of water quality impacts associated with extremes.

Data needs, especially local level data and tools

- Maintain and enhance, where necessary, the climate and streamflow monitoring network. The federal governments need to play a larger role in support of this activity.

- Develop better methods for generating the local-level output and projections most needed by practitioners. Coarse resolution of existing models misses much significant detail: surface-atmosphere interactions and hydrological-biological interactions. Downscaling works poorly when local detail matters.

- Develop a "ready-to-use" climate database to be made available to local practitioners.

- Develop decision tools for use by local water planners that can be used to account for water, answer questions about the sustainability of water use relative to supplies, and incorporate climatic change in projections.

Improved modeling of water supplies

- Develop improved evaporation and evapotranspiration estimates for use in modeling.

- Develop probabilistic drought scenarios for contingency planning.

Strategies for water management and pricing

Develop a broader, more inclusive decision environment to promote more equitable and more efficient adaptive management. Currently, water management practices are fragmented: private versus public and federal versus state/province. Evaluate the effectiveness (as measured by water availability and equitable pricing) of different management and pricing arrangements.

Interaction of climate/weather impacts with other stressors on water supplies.

- Human settlement patterns and associated demands on water exert greater stress on the system than climate/weather impacts. Evaluate the impacts on water supplies of the interaction of climate extremes with changes in settlement patterns.

- Identify social and economic trends altering demands and influencing the vulnerability of system outputs (water for agriculture, recreation, power, and human consumption) to climate extremes.

Issues related to water quality and climate / weather extremes

- Determine how extreme weather events (*e.g.,* heavy downpours and flooding, prolonged drought, or extreme temperatures) affect water quality.

- Examine how changes in climate and climate variability affect:
    - Nutrient loads in freshwater systems
    - Sediment loads in freshwater systems
    - Toxic pollutants in freshwater systems
    - Microbial pathogens in freshwater systems
    - Degradation or physical alteration of aquatic habitats
    - Water temperature and stream flow

- Investigate how new datasets (*e.g.,* remote satellite sensing of land cover) and new tools (*e.g.,* Geographic Information Systems) can be used to analyze the effects of climate extremes over time on water quality, and how data from different monitoring networks can be effectively aggregated.

IMPACTS on INFRASTRUCTURE

The impact of extreme events on infrastructure is significant and growing as economies prosper and people increasingly live and work in vulnerable areas (*e.g.*, coastal and waterfront areas). Suggestions for research included insurance industry requirements, modeling of complex-composite events, and development of decision tools for long-range infrastructure planning.

Research needs identified by insurance industry

Develop estimates of the probability distributions of the "extremes of extremes" *e.g.,* massive hurricanes. These estimates should periodically be updated.

Modeling complex-composite events

Structural failures are hardest to predict in "coupled" or "complex-composite" events (*e.g.*, heavy rain on snow/ice). Climate change may change the frequency, distribution and duration of such coupled events. Develop models to project potential changes in structural failures for coupled events.

Suite of models to enable smart planning decisions for major infrastructure

Major infrastructure is planned for time scales on the order of 50-100 years. Develop a suite of models yielding a generally consistent range of possibilities upon which long-term planning could make educated guesses, *e.g.*, about the extent of sea level rise, the likelihood of extensive droughts.

COMMUNICATION ISSUES

The need for improved communications across communities of scientists and with communities of practitioners was a common theme during the meeting. Several specific ideas for research or work in this area were suggested, including:

- Bridge the gap across professional communities between computer designers and climate modelers, and between climate modelers and impacts modelers. Standardize or harmonize language and data and agree upon the questions and information requirements that most need attention.

- Incorporate operational knowledge (the experiences of managers of systems that are threatened by extreme events) into a modeling framework for extremes and their impacts.

- Develop interactive approaches linking operations and research participants focused on understanding problem definition, framing, and symmetric learning between the two groups.

- Develop communications strategies for conveying to citizens and decision makers the capabilities and the limitations of scientific models and projections, and the uncertainties surrounding particular projections.

CONCLUSION

Several important messages were conveyed during the course of the symposium. The need for ongoing binational and collaborative efforts was recognized by participants from the various scientific and practitioner communities. Many of the research needs identified can only be effectively addressed by multidisciplinary and multinational research teams. As important as the need for collaboration is the recognition that this agenda will require the financial support of a variety of funding sources. Public-private partnerships must be forged if these research needs are to be addressed.

The success of this symposium in bringing together diverse communities of researchers and stakeholders suggests the importance of continued, periodical reporting in similar fora. As researchers move to respond to the information needs of resource managers, policy makers, and other practitioners, the science of climate change and climate/weather extremes will intersect the needs of affected communities. Research at the interface of traditional science and the practical needs of communities, of resource managers, of planners and developers, of emergency preparedness officials, and of local, state, and federal policy makers is research whose time has come.

APPENDIX A: Symposium Organization

DAY ONE: SETTING the STAGE

The meeting took place over three days. The first day introduced the climatic and societal contexts of extreme weather. Sessions included:

- current capabilities for identifying weather extremes in the climate system;
- understanding extreme weather in the context of climate change; and
- society's vulnerabilities to weather extremes

Each session was organized around a series of questions. The central question for every session — "What are the gaps in our knowledge that should or could be tackled in the next 3, 5, and 10 years? And, what recommendations would you make for addressing these gaps?" — was the source of vigorous discussion and forms the underpinnings of this report.

The first session on current capabilities addressed several other questions, including::

(1) How does one define an extreme weather event? What do we know about extremes in the US and Canada in terms of spatial and temporal occurrence, intensity, etc.?
(2) What do we know about historical trends in weather extremes in the US and Canada?
(3) What factors limit our understanding and contribute to uncertainties surrounding current and historical extremes?

Bill Hogg (Environment Canada) noted the difficulty with which we define climate extremes. He observed that "there are as many ways of defining extreme climate as there are investigators analyzing the problem." David Easterling (National Climatic Data Center) suggested that the development of indices that combine and simultaneously track a suite of climatic measures (like that introduced by Tom Karl in 1996 for the United States [1]) may improve our characterization of extreme events.

Later that day, the focus turned to understanding extreme weather in the context of climate change. Questions from the second session included:

(1) What is the state of the science with respect to understanding how climate change may affect (exacerbate or ameliorate) extreme weather in North America, including changes in the type, frequency, intensity, duration, or location of extreme weather events?
(2) How well do existing climate models duplicate the historical records (with respect to spatial and temporal occurrence, intensity, etc.)?
(3) How useful are existing climate models for simulating weather extremes? Does the utility of the models vary depending on the type of event?
(4) What is the uncertainty (origin and extent) associated with the models? What factors limit our understanding and contribute to uncertainties in describing the relationship between climate change and extreme weather?

Work simulating extremes within GCMs (General Circulation Models) is beginning to advance our understanding of extremes in the context of climate change. Francis Zwiers

[1] Karl, T.R., R.W. Knight, D.R. Easterling, and R.G. Quayle. 1996. Indices of climate change for the United States. *Bull. Amer. Meteor. Soc.* 79:1107-19.

reported on an extreme value analysis of equilibrium and transient change experiments performed with the Canadian Climate Change Model 2 (CCC GCM2) and its coupled version, CGCM1. He found that this model simulated extremes that "bear at least some resemblance to those of the real world," with relatively small differences in extreme temperature changes simulated in equilibrium and transient runs and larger differences in extreme precipitation changes. Much work remains, but progress has been made including the efforts of a number of labs comparing extremes simulated by two or more models. The research needs outlined during this session reflect a widely-held sense that comparative studies utilizing a wide range of GCMs will be necessary to better understand the capacity and limitations for modeling extremes with the present generation of GCMs. Yet, Ian Rutherford (Canadian Institute for Climate Studies) cautioned: "Don't look for extremes of the type associated with severe convective phenomena such as tornadoes or even hurricanes until models have sufficient resolution to represent them properly."

The third segment of day one focused on society's vulnerabilities to weather extremes. The questions considered in this session included:

(1) What is the range of potential physical effects of extreme weather events, *e.g.,* wild fire, heat waves, drought, flood, mudslides, wind storms?
(2) What makes an extreme event a disaster?
(3) In what ways are human systems vulnerable to weather extremes? What are the particular vulnerabilities of American and Canadian societies?
(4) What is the relative role of climate and non-climate factors (*e.g.*, social, economic, political, and institutional contexts) in defining society's vulnerability?
(5) Are there trends in society's vulnerability? What role does climate change play in those trends? What role does change in non-climate factors play in those trends?

David Etkin (Environment Canada) noted that "it is important to distinguish between the cause of a disaster and its trigger." Severe storms may trigger disasters but the cause is invariably more complex and is related to "all the social processes that create vulnerability." Confusing "cause" and "trigger" alters perceptions of responsibility and may delay or halt effective prevention efforts. Etkin stressed the importance of "creating a society with more local resilience to disasters" as a means of buffering against risks of future disasters.

Mary Fran Myers (University of Colorado) noted that there is a separation between hazard issues and other community issues that prevents local communities from developing more integrated, interdisciplinary problem-solving approaches to risk. She contends that "an approach is needed to forge local consensus about disaster resiliency and nurture it through the complex challenges of planning and implementation."

DAY TWO: SOCIETAL IMPACTS

The second day of the meeting moved into break-out sessions focused on the impacts of extreme events on human health, air quality, water supplies, and infrastructure. In each session, presenters were asked to discuss the topic from either a "science and assessment" perspective or an "operations and policy" perspective. Presenters were asked to describe present research directions and to identify near, medium, and longer term research needs. The "science and assessment" perspective addressed the following questions:

(1) What does the historical record show regarding the vulnerabilities of North American water supplies (or air quality, or human health, or infrastructure) to weather extremes?
(2) What changes in weather patterns may be expected to have the greatest impact on water supplies (or air quality, or human health, or infrastructure)?
(3) What non-climate factors impact the ultimate vulnerability and adaptive capacities of water supplies (or air quality, or human health, or infrastructure) to extreme weather?

The focus for the "policy and operations" perspective was slightly different. Questions considered by these presenters included:

(1) What is the role of weather and climate in water supply (or air quality, or human health, or infrastructure) operations, planning, and policy?
(2) What characteristics of extreme weather are most important in an operations or policy context? What aspects of operations are most vulnerable to extremes?
(3) What changes in management practices, resource demands, or other non-climate factors (*e.g.,* land use, population distribution, political and economic contexts) may be expected to influence the vulnerability of water supplies (or air quality, or human health, or infrastructure) in North America to extreme weather?
(4) How do the operations and policy communities use weather or climate information? What factors limit the value or utility of this information for their purposes?
(5) What sort of weather or climate information would be most useful if it were available?

During this session, Roger Pulwarty (NOAA) noted that "How well water systems handle the extreme tails of current or altered climate distributions is likely to be an overriding concern as systems become more constrained." With respect to air quality issues, Carmelita Olivotto (Environment Canada) concluded that "very little connection is made between air quality science and global atmospheric issues... Leadership and planning are required to direct the integration of air quality and weather extremes science."

DAY THREE: SETTING an AGENDA for PROGRESS

Day three of the symposium concluded with discussions about advances in impacts and vulnerability modeling, in global and regional climate modeling, and in computer speed and architecture. Day three deliberations demonstrated the many challenges that remain along the frontiers of these disciplines in understanding extreme events. The lack of coordination among these three communities is pronounced and progress toward meeting many research needs will hinge on better coordination and integration of efforts.

The questions addressed in the presentations and discussions related to impacts and vulnerability modeling included:

(1) What are capabilities of impacts and vulnerability modeling to replicate current conditions and to simulate future conditions?
(2) What are the uncertainties associated with

these types of models and what are the limiting factors?
(3) What sort of output from climate models would be most useful if it were available (*e.g.*, variables, synoptic climatology descriptors, temporal and spatial scale)?

According to Roger Street (Environment Canada), there are three major limiting factors that contribute to the uncertainties of impacts and vulnerability models for extreme events — scenario uncertainty, parameter uncertainty, and model uncertainty associated with gaps in scientific theory. He suggests that "greater certainty than exists now over future changes of climate and its magnitude and structure, such as extremes, could lead to major savings in infrastructure replacement and designs of weather-sensitive systems to gain greater future flexibility."

The questions related to global and regional climate modeling advances included:

(1) What are the current capabilities of climate modelers to provide the output required by the impacts modeling community?
(2) What are the uncertainties associated with current projections of extreme events and what are the limiting factors (*e.g.,* temporal or spatial scales)?
(3) What improvements do climate modelers expect to make in the future?
(4) Are there things that the impacts community requires that climate modelers believe can never be provided (owing to the complexity of the climate system)?
(5) What computational advances (physics, resolution, program structure) are required to address the identified needs of the impacts (and climate) community?

APPENDIX B: Symposium Participants

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